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Improving Satellite Surveillance through Optimal Assignment of Assets

Claire Rivett and
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ABSTRACT

To protect Austalia's economic concerns and its coastline from attack there is a need for surveillance of a large area of Australia's Sea Air Gap. Satellites have the advantage of viewing large areas of the earth regularly. Currently there is no indigenous facility to launch satellites dedicated to the surveillance of Australia. With the advent of new micro technology small nano/pico satellites are being built and launched at a fraction of the cost of conventional satellites. This has allowed for the invention and investigation of new concepts for satellite missions. For example Auspace (Tactical Satellites Study: Interim Report RTP-TACSAT-0001-AUS 17-April 2003) is investigating the feasiblity of the design of small satellites for short term misssions to be launched into low orbit on demand.
This report investigates the use of linear programming to optimise the preformance of constellations of small satellites when the constellation design for a particular misssion is known.

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Improving Satellite Surveillance through Optimal Assignment of Assets

Executive Summary

With the advent of new Micro Electron Mechanical Systems (MEMS) small nano/pico satellites are being built and launched at a fraction of the cost of conventional satellites. This has allowed for the invention and investigation of new concepts for satellite missions. For example the idea of collaborating clusters of micro satellites has been used to control arrays of satellites where the functionalitiy is distributed across a group of satellites [8]. Missions such as MIT SPHERES formation flying testbed and the Stanford ORION program are showing the benefits of distributed satellite systems. These benefits include increased survivabilitiy, reduced cost of development and easier maintance and improved revisit times and resolution. Auspace Ltd, is investigating the feasiblity of the design of small satellites for short-term misssions to be launched into low orbit on demand [9]. This report investigates the use of linear programming to optimise the performance of small satellite constellations where the constellation design for a particular mission is known. The purpose of the proposed constellations is to observe the Sea Air Gap (SAG) and performance of the constellation is measured in terms of percentage coverage of the SAG.

Work done by Auspace Ltd, which demonstrated the use of three constellations to cover the SAG was reproduced using Satellite Tool Kit (STK). STK has been used to simulate the orbit of satellites and return information about coverage of the SAG. The use of a constellation of satellites to cover the SAG has been improved with the scheduling of the sensor's elevation angle for each pass of the satellite. Several Linear Programming algorithms were used on the Auspace scenarios and in each case the percentage of coverage improved. Most notably the coverage from 8 satellites was improved to 100%, coverage; this is the level of coverage that is achieved by Auspace Ltd with 16 satellites.

These results demonstrate how careful scheduling of assets can lower the size of a constellation designed for surveillance and hence the cost of building and launching such a constellation. These methods can be extended to the design and operation of small satellite constellations used for surveillance tasks over Australia.

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Claire Rivett graduated with honours in pure mathematices from Adelaide University in 1992. From 1999 she has been working part time at Adelaide University as a tutor and marker while studying towards a Masters degree in applied mathematics. Claire joined ISRD in May 2002. Her research interests include linear and non-linear optimisation techniques and the use of heuristic search methods such as genetic algorithms and simulated annealing.

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Carmine Pontecorvo completed his undergraduate degree in Electrical and Electronic Engineering in 1994 and a Ph.D. in image processing in 1998, both at The University of Adelaide. He then went to Samsung SDS Co. in Seoul, South Korea for a year working on a surgical simulator tool. In 2000 he joined the Surveillance Systems Division of DSTO working on space-related issues, in particular.

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1. Introduction

1.1 ADF Surveillance Needs in the Sea-Air Gap

Australia needs to regularly monitor the land and maritime approaches for defence, security and economic reasons. In addition the problems of non-military attack in the form of illegal drug trafficking and immigration, fishing, piracy and quarantine infringements are raised in the 2000 White paper [3].
The Australian Defence Force (ADF) objectives, as stated in this paper, include:

- To detect, track and identify aircraft, small boats, ships and submarines day or night in all weather,
- To detect, track and identify foreign military incursions and operations on Australia's territorial lands,
- Gather strategic and tactical intelligence in Australia's area of interest, and
- Survey and map Australia's land and sea regions.

These problems require the effective surveillance, patrolling and policing of our maritime approaches. There is a push to increase ADF's surveillance capabilities to provide continuous real time coverage of the northern air and sea approaches. The surveillance resources currently available to cover the wide region of Australian interest are inadequate to satisfy all the civil and military requirements. Space-based sensors may provide part of the surveillance solution as they can observe large parts of the region very quickly.

1.2 The Surveillance Task this Paper Deals With

This report deals with the coverage of the sea air gap (SAG) by constellations of small satellites. The aim of this work was to demonstrate how optimisation techniques could be employed to improve the surveillance area covered by a sensor on an existing constellation. To develop adequate measures of the effectiveness of a surveillance system the type of surveillance tasks required of this system need to be well defined. This report only looks at the percentage area covered by a constellation during a period of 24 hours. However many other requirements such as: image resolution, revisit time and timeliness of data are important for the assessment of the quality of surveillance delivered by a system.

1.3 The Need for Native Satellite System

Satellite information obtained from allies and from commercial satellite systems is of great use for the surveillance of the Australian northern coastline. The Australian Centre for Remote Sensing (ACRES) ground stations receive commercial satellite downlinks at Alice Springs and Hobart from European ERS-1, Canadian Radarsat, French SPOT 2 & 3, and US Landsat 5 satellites. The detection of commercial, naval, fishing and pleasure vessels is possible with the satellite data obtained from these commercial satellite systems [4].

The current commercial satellites meet most of the criteria to perform maritime surveillance with the exception of suitably short revisit times that enable the tracking of targets. Furthermore the many different demands placed on allied surveillance systems may mean that the delivery of information requested by Australia is not

delivered in time to be of substantial use. The immediate tasking of surveillance assets to Australia's surveillance requests may not be possible.

With the advances in "nano" and "pico" satellite technology the cost of developing and launching satellite systems has dramatically decreased allowing more nations to participate in the development of space technologies.

For example Algeria's first national satellite AISAT-1 was launched in Northern Russia on 28 November 2002. This satellite is the first of an international Disaster Monitoring Constellation (DMC) that is lead by SSTLexpand this [6]. The satellite was designed and constructed by SSTL at the Surrey Space Centre (UK) in collaboration with the Algerian Centre National des Techniques Spatials

A "DMC consortium" comprising of partnerships between organisations in Algeria, China, Nigeria, Thailand, Turkey, Vietnam and the United Kingdom has been formed to develop and build the DMC constellation. This collaboration has made it affordable to develop a highly capable constellation of micro satellites at a fraction of the cost of a conventional satellite.

2. Nano- and Pico-Satellites

2.1 What are they?

Nano and Pico satellites are commonly taken to be satellites under 10 kg and 1 kg weight respectively. Recent research is developing nano/pico satellites of two types, those satellites that have the same capabilities as larger satellites and those small, capable satellites with the specific development revolutionary designs. The integration of technologies and manufacturing techniques developed for the micro-electronics industry has made the development of these satellites possible. The revolutionary designs of these satellites are leading to new ways of defining space tasks.

The development of nano-/pico satellites is still at an early stage. Many of the nano-pico satellites, that have been launched, have been developed by Universities and have limited capabilities and lifetime.

2.2 How They Can Help the ADF

Advantages to the ADF of having small satellites include:

- Lower mission costs: smaller mass systems; lower launch costs, and less expensive engineering philosophy.
- Demonstrations prior to significant investments in operational capability are now possible.
- Smaller systems can be built and launched in shorter time scales. The development of launchers for small satellites makes an indigenous launcher within Australia's reach.
- There can be more rapid replacement of damaged systems, i.e. more built in large-scale redundancy.

Lower costs and shorter design lifetime can aid with the rapid upgrade of the satellites with newer technologies as they emerge.

3. Auspace Report

3.1 Introduction

The Auspace report [1] addresses issues surrounding the use of nano/pico satellites for a variety of military and civilian applications. Of particular interest is the coverage of Australia's SAG (see Figure 1), which may be inexpensively achieved through the use of nano/pico satellites. To obtain a resolution suitable for military purposes Auspace suggests in their report the use of along track interferometry. Interferometry exploits the images returned by two satellites, which are separated by a small time interval, travelling along the same ground track. Note that only a single satellite is used by Auspace to model these satellite pairs.

In Chapter 8 [1] the area coverage of a target area by a small constellation of nano and pico satellites is dealt with in detail. Auspace calculated the percentage coverage of the target area of Figure 1 achieved by one, eight and sixteen satellites over a period of 24 hours.

Three different scenarios, as considered by Auspace, were reproduced as Satellite Tool Kit (STK) "scenarios" for optimisation. These scenarios are:

- One satellite with inclination 20°, altitude 461.96 km and Right Ascension of Ascending Node (RANN) 0°.
- A constellation of eight satellites equally spaced over a single orbital plane of inclination 20°, RANN 15° and altitude 461.96 km.
- A constellation of sixteen satellites equally spaced over 2 orbital planes of inclinations 20° and 15°, altitudes 461.96 km and 459.30 km and RAANs of 15° and 30°, respectively.

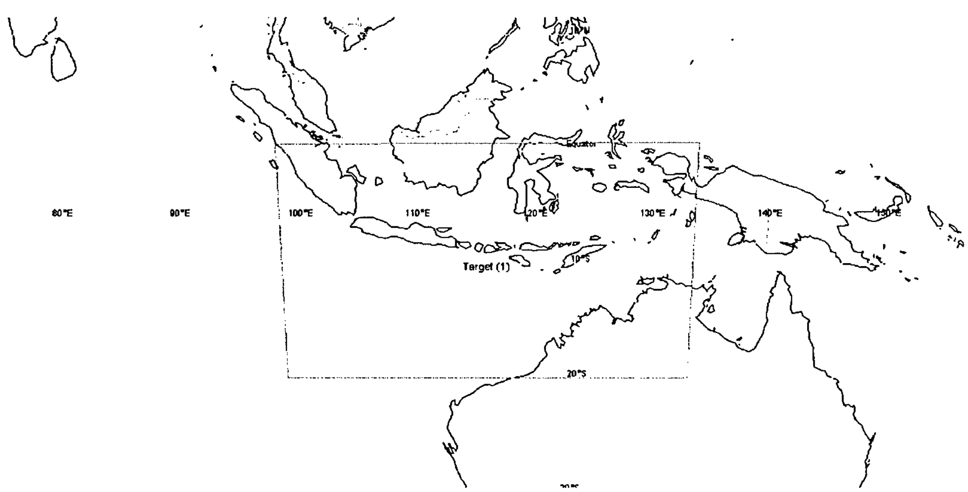

Figure 1: The region of Interest over the Sea Air Gap (SAG)

3.2 Reproduction of Results using STK

To reproduce Auspace's coverage results the same target area has been modelled and the same scenarios have been created using STK.

3.2.1 Assumptions

The following assumptions were made when creating the scenarios in STK:

a) The interferometry provided by a pair of satellites is modelled with one satellite.

b) The radar operates in "Scansar" mode. This mode operates with two, three or four beams during data collection. The beam switching rates are chosen to ensure each beam gets a look at the Earth's surface within the along track illumination time (dwell time) of the antenna beam. Therefore the sensor has an effective swath width of 60 km produced by three operational beams [5]. The ScanSAR (Wide) mode covers a nominal area of 500x500 km^2 and has a nominal resolution of 100 m.

c) The sensors ground range is 196 km to 726 km to the left hand and right hand sides of the ground track. The angle of elevation of the sensor attached to the orbiting satellite is varied to produce 10 different swaths 60 km each to the left or right of the satellite's ground track. Neighbouring swaths overlap by 7.5 km.

d) A single swath is chosen for each pass of the satellite based on which choice would produce the longest ground track. Assume the swath, which returns the longest access duration time, produces the longest ground track.

e) The area target's coordinates are:

Latitude (degrees)	Longitude (Degrees)
-20	135
-20	100
1	100
1	135

3.2.2 Modelling the Sensors with STK

The different swaths available to a sensor have been modelled using some of the basic properties of a sensor's footprint that can be set in STK. These basic properties define the sensor footprint's shape, dimensions and position relative to the satellite's ground track.
The sensors in this scenario are modeled as in Table 1.

Table 1: Sensor Definition.

Shape	Rectangular
Dimensions	Vary the horizontal half angle to maintain a 60 km swath width as the elevation angle changes.
Swath	The elevation angle is varied to create 10 different swaths either left or right of the ground track. The azimuth is set at -90° or 90° when the sensor looks left or right of the ground track respectively.

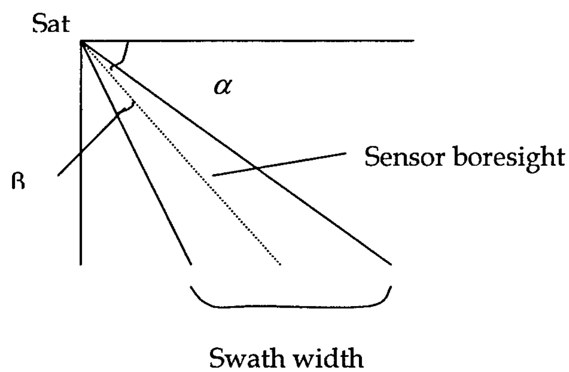

Figure 2 Sensor Geometry

Figure 2 shows the basic sensor geometry of the sensor. α is the elevation angle of the sensor while β is the sensor half angle. As the sensor elevation changes the sensor half angle is changed to ensure that the swath width remains 60 km wide.

There are 20 different swaths, 10 on ether side of a satellite's ground track, created by the sensor settings or swaths described above. Figure 3 shows the rectangular footprints for different sensor elevation angles produced by a sensor on the satellite SAR_s2. A pointing schedule for a sensor is the series of sensor settings chosen over a period of 24 hours. A sensor setting is chosen for each pass of the satellite or satellites over the access target. Only one pointing schedule is found for all sensors in a constellation.

Half angles used to model the footprint vary with the elevation angle used to maintain constant swath width. When calculating these half angles the effect of distortion due to the Earth's curvature is not taken into account. Table 2 below lists the possible swaths, which can be selected from a sensor.

Table 2 Half angles and ranges for swaths with an overlap of 7.5 km.

Swath	Min Range	Max Range	Half Angle	Elevation Angle
1	196.0	256.0	3.01	63.83
2	248.5	308.5	2.73	58.81
3	301.0	361.0	2.46	54.26
4	353.5	413.5	2.21	50.18
5	406.0	466.0	1.97	46.53
6	458.5	518.5	1.76	43.28
7	511.0	571.0	1.57	40.37
8	563.5	623.5	1.40	37.78
9	616.0	676.0	1.26	35.45
10	668.5	728.5	1.13	33.37

The 10 swaths of 60 km width with a 7.5 km overlap will not fit into the sensor's access zone prescribed by Auspace.
Table 3 lists swaths produced when the overlap is 7.777 km.

Table 3 Half angles and ranges for swaths with an overlap of 7.77 km.

Swath	Min Range	Max Range	Half Angle	Elevation Angle
1	196.0	256.0	3.00	63.93
2	248.2	308.2	2.73	58.94
3	300.4	360.4	2.46	54.42
4	352.7	412.7	2.21	50.36
5	404.9	464.9	1.97	46.73
6	457.1	517.1	1.76	43.48
7	509.3	569.3	1.58	40.58
8	561.6	621.5	1.41	37.99
9	613.8	673.8	1.27	35.66
10	666.0	726.0	1.30	33.80

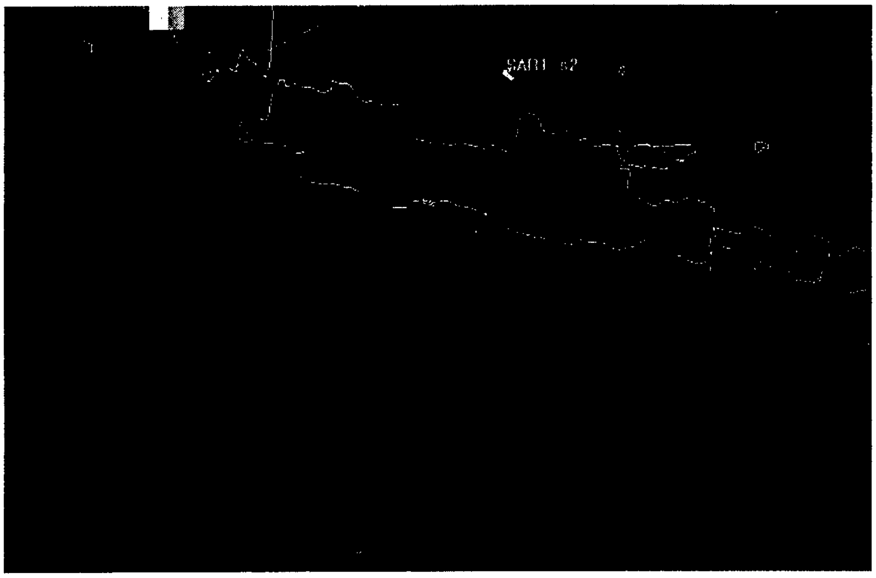

Figure 3 Illustrates the different rectangular sensor footprints produced by different sensor elevations. SAR1_s2 is the satellite travelling along its orbit.

3.2.3 STK Algorithm Used for Comparison

When considering a single satellite the Auspace algorithm chooses a single sensor setting for each pass of the satellite based on which swath produces the longest ground track across the region of interest. The STK algorithm models this by choosing the sensor setting which gives rise to the largest number of accesses to the target area's grid points since a target area is modelled in STK by this grid of points.

One sensor setting per satellite pass is allowed for all assets in the 8 satellite and 16 satellite scenarios. This sensor setting is chosen such that the largest total area covered by all satellites at a fixed setting is found.

3.3 Comparison

Table 4 compares the percentage area coverage obtained by Auspace with the results produced by STK for the three scenarios used. The table lists the percentage of the target area visited between 1 and 10 or more times for each scenario modelled.

Table 4: Percentage area covered by Auspace and STK Algorithm and the difference between area coverage for each constellation used in this report.

	One Satellite			8-Satellite Constellation			16-Satellite Constellation		
Visits	AUSP	STK	Δ	AUSP	STK	Δ	AUSP	STK	Δ
1	21.05	23.07	2.02	31.92	25.36	-6.56	6.98	3.50	-3.48
2	1.49	5.53	4.04	25.66	16.06	-9.60	17.58	9.84	-7.74
3	0	0.16	0.16	14.62	18.19	+3.58	23.31	16.00	-7.32
4	0	0	0	7.82	13.38	+5.56	20.08	11.98	+8.10
5	0	0	0	3.12	8.19	+5.07	13.47	13.64	+0.17
6	0	0	0	1.36	3.12	+1.77	7.63	13.38	+5.75

7	0	0	0	0.65	1.72	+1.07	4.52	10.96	+6.44
8	0	0	0	0.18	0.45	+0.27	2.50	7.04	+4.55
9	0	0	0	0.07	1.05	+0.98	1.34	3.63	+2.29
10+	0	0	0	0.02	1.43	+1.41	1.44	9.72	+8.28
Total	22.55	28.70	6.06	86.62	88.95	+2.33	98.85	98.69	-0.16

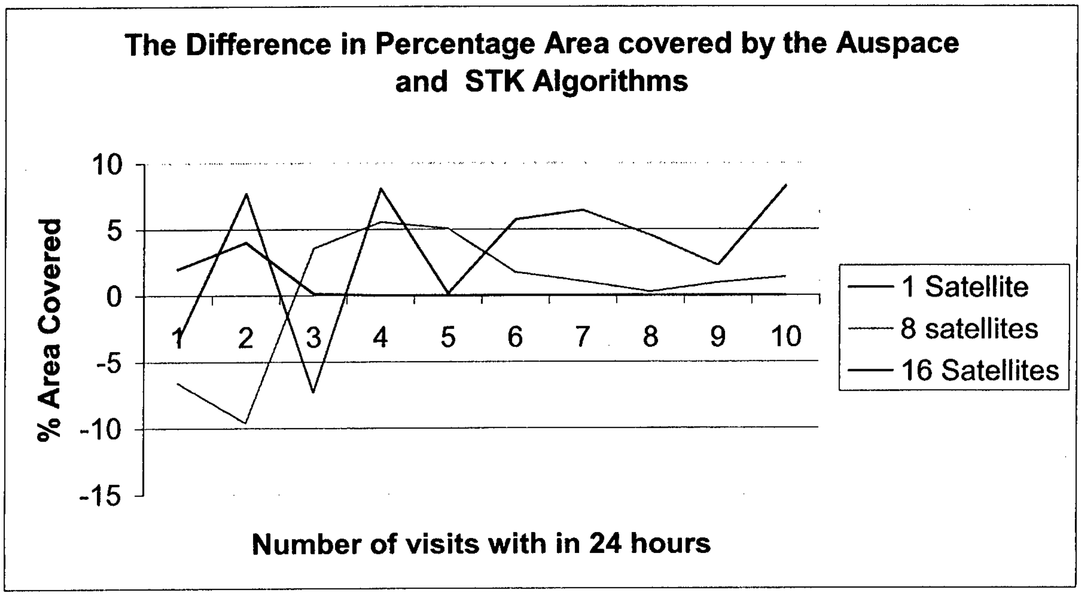

Figure 4 The differences in Percentage are covered by Auspace and STK algorithms for constellations of 1, 8 and 16 satellites

Differences between the STK and Auspace results are:

- For the 1-satellite and 8-satellite cases the area seen by STK exceeds that observed by Auspace.
- In the 16-satellite scenario the STK model has more visits to the target area than the Auspace model; however, the total percentage of area covered over the 24-hour period is sightly less. (See Figure 4)
- The percentage of area accessed multiple times by the STK model is distributed differently from the Auspace results over the number of visits for the 8-satellite and 16-satellites cases.
    1) The percentage of area visited 3 or less times by the STK model is less than the Auspace model.
    2) The percentage of area covered more frequently than three times by the STK model is consistently larger than Auspace's values.

Nevertheless, the discrepancies between the STK and Auspace results are all less than 10%.

3.4 Sources of error

Possible sources of errors in the percentage area covered in Table 4 are:

1) The model used by Auspace to propagate their satellites did not take into account drag on the satellite and the effect of the oblateness of the Earth has on a satellite's orbit whereas the STK propagation model used did. This will affect the shape of the orbit and change the satellite's altitude and hence the exact location of the sensor footprint on the Earth's surface.

2) The sensor footprint was modelled as a rectangle with a width of 60 km. This footprint maintained a constant width regardless of the sensor's elevation angle. As the sensor's elevation angle decreases any error in the half angle used to define the sensor's footprint in STK increases errors in the footprint's width. As the ground range for each sensor was between 196 km and 726 km, the errors in the sensor footprint's size may have been introduced when the sensor operated at the upper limit of this range due to the curvature of the Earth.

3) Auspace claimed their swaths were overlapping by 7.5 km. However 10 swaths, each 60 km, wide do not fit into the ground range given by Auspace. The swath overlap used to obtain the STK results was 7.77 km. When this overlap is used 10 swaths will fit into the ground range as quoted in the Auspace report [1].

4) The method used to model the target area could influence the coverage results. STK uses a point grid to represent the target area. These grid points are 0.5 of a degree apart, which amounts to approximately 55 ground kilometres. Therefore each point in the grid is at the centre of a cell of approximately 3025 km^2. Auspace's criterion for choosing a sensor's elevation angle was the sensor setting that produced the longest ground track across the target area. In STK we have modelled this choice of sensor setting by choosing the sensor setting that accesses the most points in the target area. It is possible that STK returns accesses to points representing 3025 km^2 of area when in fact the sensor may have only seen half of this square. Reducing the dimension of the target area's point grid should deal with these sorts of inaccuracies, however the amount of computation time required for smaller grid spacings increases dramatically.

4. Alternative Algorithms for the Pointing Schedule

When considering coverage of the sea air gap for surveillance there are a number of factors, which can be analysed to access the quality of surveillance delivered. These include the percentage area of coverage, access duration, and revisit time, resolution and the probability of detections. The target area is 78,357,517km^2. The sort of coverage issues addressed for larger target areas are the percentage coverage of the target area and time taken to revisit the whole or important parts of the target area.

Percentage coverage of the target area and the spread of multiple coverage over the target area is considered below.

4.1 Longest Ground Track (LGT)

When considering a single satellite the Auspace algorithm chooses a single sensor setting for each pass of the satellite based on which swath produces the Longest Ground Track (LGT) across the region of interest. The STK model of this algorithm chooses the setting which gives rise to the largest number of accesses to the target area's point grid. Choosing the set of longest ground tracks for a satellite will ensure that the maximum area is covered in each pass however it does not ensure that maximum area is covered over the 24 hours. By choosing the set of largest ground tracks, sections of the region may be covered several times while areas in close proximity to these longest ground tracks are never accessed.

The LGT algorithm can be used by considering all sensors of a constellation as the one surveillance asset with a common pointing schedule. For each pass the access areas from each sensor of each satellite of the constellation are added. Then the sensor setting delivering the largest area covered for a particular pass becomes part of the pointing schedule. We call this "algorithm 1". The results from this algorithm are compared with of results from Table 4 in Section 3.3.

This algorithm considers the coverage given by choosing a sensor setting for all sensors in the constellation during a pass. It may be beneficial to create separate pointing schedules for each satellite of the constellation. The separate pointing schedules are still based on the set of longest ground tracks for each satellite in the constellation rather than maximising the area seen collectively by all whole constellation during a pass. This selection method will still produce some areas that are covered multiple times while areas in close proximity to the longest ground tracks are never accessed. The results of this "Algorithm 2" are very similar to the results of "Algorithm 1". A comparison is shown in Figure 5.

The total percentage of area covered from algorithm 2 is slightly worse than that of algorithm 1. (Note the percentage of total area visited 0 times in Figure 5). There are more points seen multiple times as the LGT is chosen for each individual sensor without considering which points other sensors in the constellation have already accessed. The sensors are not acting cooperatively to cover the largest area.

The algorithms producing the results in Table 4 and Figure 5 have been implemented using Matlab.

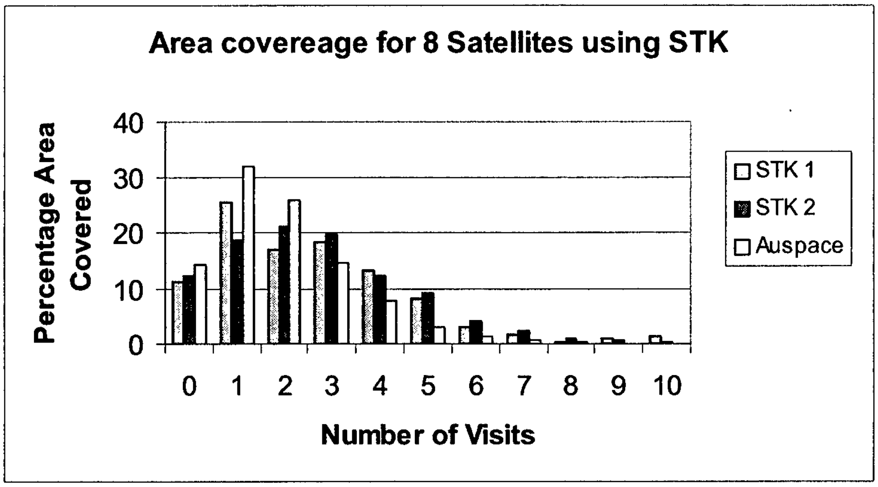

Figure 5 Coverage results for STK Algorithms 1,2 and Auspace for the 8-satellite scenario

4.2 Maximum Total Area Accessed

If target area points accessed during the simulation by each satellite of a constellation can be kept track of, then the total area accessed by all satellites in the simulation can be maximised.

To implement the maximum area algorithms, the optimisation software ILOG Studio has been used to search for the best combination of access sets that produce the maximum area coverage. These problems are formulated as Linear Integer Program (LIP).

When choosing which algorithm is needed to define the best pointing schedule for the assets used in coverage it is important to define carefully what the coverage objectives are. This report has focused on the percentage area covered and only indirectly on how multiple visits are distributed over the target area.

To maximize the area seen the LIPs developed have an objective function which maximizes the sum of the points seen. The objective function is

$$F = \sum_{p=1}^{N} C_p$$

$C = \{C_1, ...C_p ...., C_n\}$ and $p \in \{1...N\}$ is a Boolean array where, $C_p = 1$ if point p has been seen and $C_p = 0$ otherwise, N is the number of points in the target area.

The computation time required to solve the LIPs depends on the formulation of the LIP. If the formulation of the problem is poorly designed then the computation time required to solve the same problem can greatly increase. Three formulations of the ILOG algorithms are discussed below.

4.2.1 One Satellite

Consider the problem of maximizing the total area covered by a single satellite over the period of 24 hours. The target area is modelled in MATLAB as an array where each cell in the array represents an area of the SAG by a point $p \in \{1 \ldots n\}$.

We define the following objects:

- Let r_j, $j = 1 \ldots M$ be the j^{th} satellite pass over the period of the simulation, where M is the total number of passes.
- The satellite sensor can be fixed at one of the available swath settings $s \in \{1,\ldots,S\}$ on each of the passes r_j. The swath choices for each pass are stored in the matrix $X_{j,s}$.
- The set of points accessed by the satellite with swath setting s during pass r_j is given by the array $A_{j,s,p}$ for $p \in \{1,..,L\}$ where L is the number of points in the target area.
- NC_j is the number of points seen during pass r_j.
- When a point has been accessed this is flagged by placing a 1 in the array $PC_{j,p}$ of type Boolean. $PC_{j,p} = 1$ when point p is accessed during satellite pass r_j and $PC_{j,p} = 0$ otherwise.
- C_p is an array of type Boolean containing accesses that have occurred over the period of simulation.

The objectives are to maximize the total area accessed by the satellite over a period of 24 hours and ensure multiple accesses are spread as evenly as possible over the region of interest which is represented by a two dimensional grid of points.

The objective function is:

$$\text{Maximize } F = \sum_{p=1}^{N} C_p .$$

The constraints are:

- Only one swath can be chosen for each pass

$$\forall j, \sum_{s=1}^{S} X_{j,s} = 1$$

- The numbers of points accessed in each pass

$$\forall j, \sum_{s=1}^{S} \left(\sum_{p=1}^{N} A_{j,s,p} X_{j,s} \right) = NC_j$$

- The set of points accessed in each pass are given by

$$\forall p, \forall j, \forall s, (A_{j,s,p} X_{j,s} \leq PC_{j,p})$$

- The number of points chosen for $PC_{j,p}$ must equal the number of points seen in each pass.

$$\forall j\,,\ \sum_{p=1}^{N} PC_{j,p} = NC_j$$

- Points accessed once or more are recorded in the Boolean array C_p.

$$\forall p\,,\ \sum_{j=1}^{M} PC_{j,p} \geq C_p$$

The computation time required to solve the LIPs with ILOG is substantially more than for the Matlab algorithm. For the one satellite case there are over 50,000 variables and 944,000 constraints in the simplex formulation.

4.2.2 Constellations of satellites

4.2.2.1 ILOG Algorithm 1

In this algorithm (ILOG-1), the target area points accessed during a pass by a satellite of a constellation are kept track of and the total area seen by all satellites during a single pass is maximised. The LIP of this algorithm has been split up into sub-problems. Each sub-problem optimises the area covered by the assets of the constellation during a single satellite pass.

The setting chosen for a sensor during some pass may not necessarily be the sensor setting that obtains the longest ground track. When this algorithm is implemented there should be no point of the target area not ever visited merely because it fails to lie on one of the longest ground tracks.

As with the STK algorithms, the target area is modelled as an array where each cell in the array represents a point of the target area.

4.2.2.2 Formulation of ILOG Algorithm 1 for Constellations

We begin by defining the following objects:

- The constellation consists of satellites sat_a, $a \in \{1,\ldots,T\}$ with p_j, $j = 1..M$ satellite passes.
- The satellites sensors can be fixed at one of the available swath settings $s \in \{1,\ldots,S\}$ on a pass. The swath choices for each pass are stored in the matrix $X_{a,s}$.
- The set of points accessed by a satellite sat_a with swath setting s is given by the arrays $A_{a,s,p}$ for $p \in \{1,..,N\}$ where N is the number of points in the target area.
- The set of points seen by an asset during a pass is stored in the Boolean array $PC_{a,p}$. $PC_{j,p} = 1$ when point p is accessed during satellite pass r_j and $PC_{j,p} = 0$ otherwise.
- The set of points seen during a pass is stored in the Boolean array C_p.
- The number of points seen by each asset during a pass is stored in AC_a
- R is the region of interest.

The objective is to maximize the total area accessed by the satellite over a pass. For example,

$$\text{Maximise}\, F = \sum_{p=1}^{N} C_p \, .$$

The constraints are:

- Only one swath can be chosen for each asset of the constellation during a pass

$$\forall a,\ \sum_{s=1}^{S} X_{a,s} = 1$$

- The number of points seen by each asset during a pass is

$$\forall a,\ \sum_{s=1}^{S} (\sum_{p=1}^{N} A_{a,s,p}) X_{a,s} = AC_a$$

- The set of points seen of each asset during a pass are calculated as

$$\forall p, \forall s,\ \forall a,\ (A_{a,s,p} X_{j,a} \leq PC_{a,p})$$

- The size of the set of points chosen by each asset must equal the number of points seen by each asset.

$$\forall a, \sum_{p=1}^{N} PC_{a,p} = AC_a$$

- The points set of points accessed during a pass are given by

$$\forall p, \sum_{a=1}^{L} PC_{a,p} \geq C_p$$

Each of these sub-problems is approximately half the size of the problem for the one satellite case, with approximately 25,000 variables and 500,000 constraints. It takes 42 hours and 36 minutes to solve the 8 sub problems of ILOG algorithm 1 for the 8-satellite case.

4.2.2.3 ILOG Algorithm 2

Consider the problem of maximizing the total area visited by all satellites of a constellation during the entire simulation. The objective function remains the same as that of ILOG algorithm 1. While these algorithms will maximize the area covered over the simulation period we expect the average revisit time of points accessed in the target area to be worse than the average revisit times afforded by the LGT algorithms. Average revisit times to points seen increase as the total number of points seen increases since there are less points seen multiple times, and points that are seen more than once are visited less.

The formulation of ILOG algorithm 1 has not taken advantage of the data's structure. The data can be represented as a series of large sparse matrices. ILOG's OPL optimisation language has functions that can manipulate sparse data structures. This representation of the data reduces memory used by OPL and the computation time. We call this ILOG Algorithm 2 or ILOG-2.

4.2.2.4 Formulation of ILOG Algorithm 2

We define:

- For each pass there is an array $A_{a,s}$ of sets, where a is the number of assets $a = 1..8$ and $s \in \{1,...,S\}$ is the swath number and S is the number of swath choices. The sets in $A_{a,s}$ are sets of the points seen by asset a when using swath s.
- Each asset in the constellation can be fixed at one of the available swath settings $s \in \{1...S\}$ on a pass.
- The swath choices for each pass are stored in matrices $X_{a,s}$.
- C_p the array of points seen during the whole simulation, where p is the number of points in the target area i.e. $p = 1,..,3139$.
- N_p the number of times each point is seen during the whole simulation. This array records all of the accesses to each point in the target area.

To reduce the occurrence of empty sets the following two modifications have been made:

(1) For some passes regardless of the swath setting none of the target area is seen. These passes are not included in the model.
(2) Each satellite pass only includes the swaths where at least one asset can see some of the target area.

Constraints

- Only one swath can be chosen for each asset of the constellation.

$$\forall a, \sum_{s=1}^{S} X_{a,s} = 1$$

- Once a swath setting has been chosen for an asset, the set of points seen by that asset during a pass can be extracted from the sets in $A_{a,s}$. The following constraint will count the number of times a point is accessed over the simulation.

$$\forall p(\sum_{a=1}^{T}\sum_{s=1}^{S}(p \in A1_{a,s})X1_{a,s} + ... + \sum_{a=1}^{T}\sum_{s=1}^{S}(p \in AM_{a,s})XM_{a,s})) = N_p$$

where

- M is the number of satellite passes considered in the simulation,
- $A1_{a,s}$ is matrix containing the set of points seen by an assets during pass number 1,
- $AM_{a,s}$ is matrix containing the set of points seen by an assets during pass number M,
- $X1_{a,s}$ is the matrix of swath choices for pass 1, and
- $XM_{a,s}$ is the matrix of swath choices for pass M.

If a value in $N\text{cov}_p$ is non-zero then the corresponding value of C_p is set to 1. C_p is an array of binary variables containing the set of points that are seen during the algorithm. An "if " statement is not a linear constraint. Introducing binary variables can linearize non-linear constraints of this type. The binary variable in this situation will contain the very information we want C_p to contain.

$$\forall p,\ NC_p - C_p Max \leq 0$$
$$\forall p,\ NC_p + (1 - C_p) Max \leq 0$$

where *Max* is the maximum number of times a point could have been seen during the whole simulation i.e. Max=(number of satellite passes) x (number of assets).

The last constraint can be simplified to

$$\forall p,\ C_p \leq NC_p.$$

To further decrease the solution time several LIP settings were changed from the default. When ILOG recognizes a linear program it will access "CPLEX". CPLEX builds a tree of problem nodes for the LIP. The LIP settings can control the order in which the problem tree is searched, how the next node to be solved is chosen, which method is used to solve the problem and sub-problems, and the emphasis of the run.

The settings used for ILOG -2 are listed in Table 5.

Table 5: ILOG settings used for ILOG-2 algorithm.

MIP emphasis	Feasibility over optimality
MIP branch	UP branch first
MIP start strategy	Primal simplex
MIP sub-problem start strategy	Primal simplex
MIP node selection	Alternate best-estimate search
Simplex pgradient	Steepest edge pricing with slack variables

When these setting were used with the sparse set formulation a near optimal solution for the formulation of the problem maximizing the coverage of 8-satellites over a 24-hour period was found in 40 minutes.

4.3 Maximising the Area Covered and the Spread of Access Points

The maximum area algorithm can be altered to consider maximizing the spread of coverage as well as total percentage area covered. The objective function maximizes the sum of the points seen. C_p is an array containing the points, which have been accessed during the simulation. If a particular point p has been seen then a "1" is placed in position p of C_p. $p \in \{1,\ldots,N\}$ and N is the number of points in the target area. The objective function is expressed as

$$F = \sum_{p}^{N} C_p .$$

To ensure these points are well spread over the target area extra terms could be added to the objective function to yield

Maximize

$$F = \sum_{p}^{N} C_p - \sum_{p=1}^{N} (TC_p - \overline{C})^2 \ .$$

TC_p are the accesses, which occur during the simulation, and $\overline{C}$ is the average number of accesses to a point in the target area. This problem is no longer a LIP. ILOG can not handle non-linear constraints on variables that, are not integers therefore an alternative tool will need to be used to search for a solution to this problem.

4.3.1 ILOG -2a

The ILOG algorithms, which maximize area coverage, will indirectly cause the spread of accesses to the target area to improve. By adding the objective to maximise the total number of accesses this spread can be further enhanced.

The objective is now a multiple objective function:

$$F = m \times \sum_{p}^{N} C_p + \sum_{p}^{N} NC_p \quad (1)$$

where C_p is the set points seen during the simulation, NC_p is the number of times each point is seen during the simulation and N is the number of points in the target area. The multiplier of $m = 30$ gives the first objective; maximize the area covered, greater priority than the second objective, to maximize the number of accesses during the simulation. Since there are only 15 passes during the simulation the maximum value that an element of NC_p can take is 15. Therefore the MIP will choose to fill up C_p in preference to obtaining multiple accesses to maximize the objective function.

Changing the value of m alters the importance of one objective over the other, which will change the optimal solution found.

4.4 Comparison of results

4.4.1 One Satellite and 8 Satellite Case

Figure 6 shows a comparison between the results for the longest ground track algorithm for one satellite and the ILOG algorithm, which maximizes area accessed over the 24-hour simulation. Figure 7 compares the longest ground track result for the 8-satellite case where each asset has its own pointing schedule and the coverage for the ILOG-1, ILOG-2 and ILOG-2a.

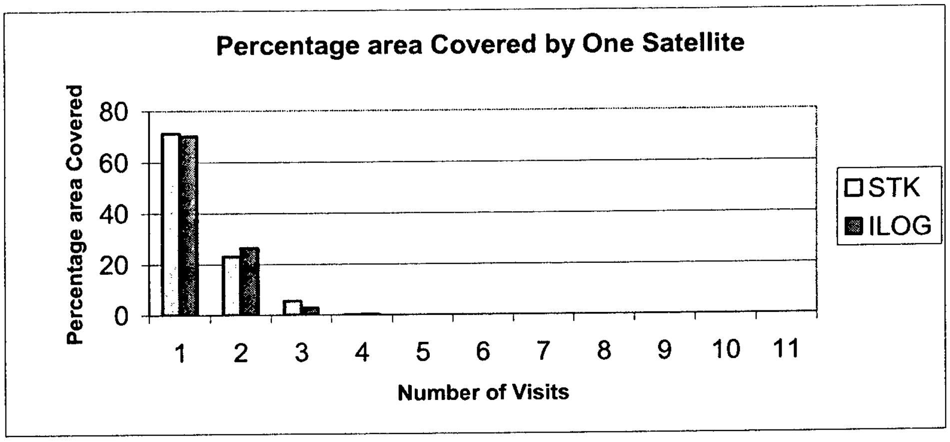

Figure 6 Percentage Area covered by one satellite when using the pointing algorithms STK (LGT) and ILOG

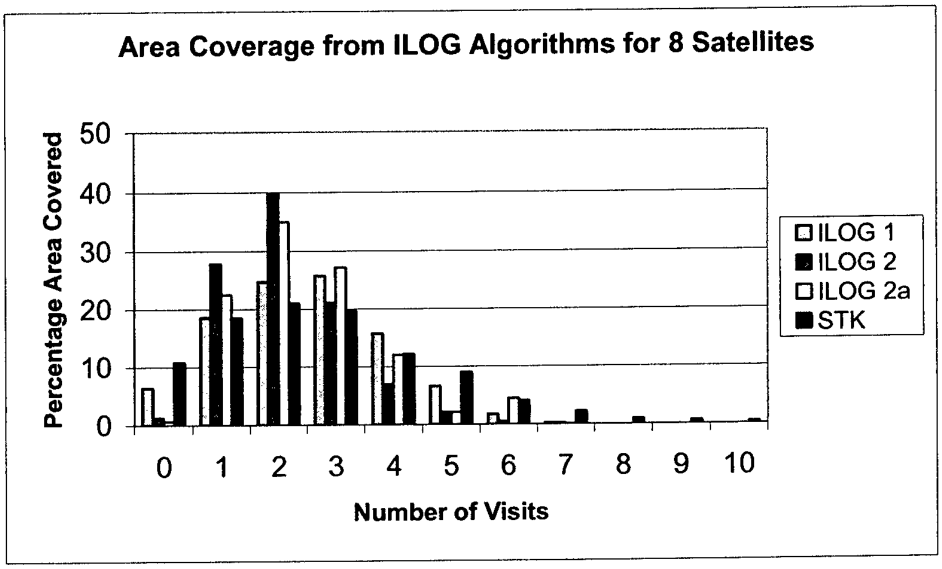

Figure 7 Percentage areas covered by 8- satellites using the pointing algorithms Stk LGT, ILOG-1, ILOG-2 and ILOG-2a

For the 8-satellite case the percentage of area covered by ILOG -1 is 5% more than the LGT algorithm and the percentage of area covered by ILOG-2 is 10% more than the LGT algorithm. The ILOG algorithms choose swaths that ensure that points that can be accessed, but have not been seen before, are accessed. This is done at the expense of choosing a swath that will maximize area accessed by a single sensor. Hence the percentage of points accessed more than 4 times has dropped while the percentage of points seen less than 4 times has increased.

When ILOG-2a is used, the spread of point accesses changes to within 6% of the spread seen in the near optimal solution to ILOG -2. Due to computation time the optimal solution to ILOG-2 was not found. This accounts for the fact that the area covered by ILOG-2 and ILOG-2a is not the same. The addition of the extra objective has decreased the search time required to reach the optimal solution with ILOG-2a,

which was found in 50 minutes. The result of ILOG-2a demonstrates that nearly 100 %of the SAG can be accessed in a single pass by only 8 satellites.

The average revisit times for the points accessed in the target area increase as the number of points seen increases. Hence the average revisit time for the ILOG algorithms is larger than for the longest ground track algorithms.

4.4.2 16 Satellite Case

The result for the 16-satellite case is shown in Figure 8. See Appendix A for the table of results. ILOG -2 covers 100% of the target area when the 16-satellite constellation is considered. The minimum number of satellites required to cover 100% of the target area is not 16. There is more than one way to choose sensor swaths that provide 100% coverage of the target area.

When the multiple objective of ILOG-2a is used then the percentage of area accessed between 1 and 10 and more times is more evenly spread over these values. The optimal solution with ILOG -2a was found in 5 seconds.

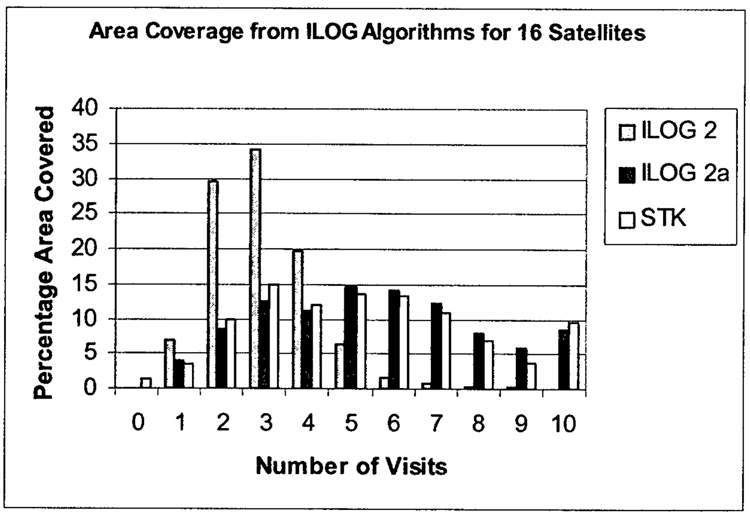

Figure 8 Percentage area covers by STK longest track, ILOG2 and ILOG2a algorithms for 16-satellite scenario

4.4.3 Sensitivity Analysis

An important issue not dealt with in this report is that of sensitivity analysis of the IP.

A linear program is defined as the minimizing or maximizing of a linear function subject to linear constraints expressed in standard form as

$$\begin{aligned} &\text{(P) Minimize } C^T x \\ &\quad \text{Subject to } Ax = b, \\ &\qquad\qquad\quad x \geq 0 \end{aligned}$$

The coefficients of (P) in the matrix A and vectors b and C will contain a set of parameters. An important issue for optimisation problems is how any deviation in the LP's parameters affects the optimal solution of (P).

Sensitivity analysis can be conducted on Linear programs with out integer constraints with the use of (P)'s dual problem (D)

$$\text{(D) Maximize } b^T y$$
$$\text{Subject to } A^T y = C,$$
$$y \geq 0$$

The Dual problem to (P) shares the same data, however, now the right hand side of the constraints in of (P) are the objective coefficients of the Dual and the objective coefficients of (P) are the right hand side of the constraints in the Dual problem.
The rate of change of the objective value as a result of changes in the right hand side vector b can be found by analysing the value of (P)'s dual variables furthermore the amount of change to the objective function coefficients which can occur before the optimum solution changes can be analysed.

This sort of sensitivity analysis cannot be done for integer programming, however a bound on the distance between the IP's solution and the relaxed LP exists [7]. In general Integer Programs are sensitive to small changes in parameter values.

The ILOG formulations have several parameters such as the number of points in the target area, the number of satellites and satellite passes and the number of swaths choices the satellite's sensor has. The sensitivity of the IP's optimum value when there are differing numbers of satellites in the constellation, different numbers of swath choices and varying number of passes could be investigated.

The formulation of ILOG2a has a multi-objective function (See equation (1) in section 4.3.1). The two criteria being optimised are the number of different points seen and the total numbers of points seen when repeat visits are counted. These objectives were weighted to make the first objective the most important. Sensitivity analysis showing how different weightings on these objectives affects the optimal objective value and the choice of swaths should be conducted to see if better coverage is achieved.

5. Discussion on Possible Optimisation Objectives

5.1 Introduction

When considering coverage of the SAG for surveillance there are a number of factors that can be analysed to access the quality of surveillance delivered. These include the percentage area of coverage, access duration, revisit time, resolution and the probability of detection. The target area modelled is $7.83x10^7$ km^2. The sort of coverage issues addressed for larger target areas are the percentage of coverage of the target area and time taken to revisit the whole or important parts of the target area.

When choosing the scheduling algorithm to find the best sensor-pointing schedule for a satellite constellation it is important to define carefully what the coverage objectives are.

If the objective were to see the entire target area at least once within a 24-hour period with the smallest number of satellites, then the extra effort of the constellation ILOG-2 would be worthwhile. If only partial coverage of the target with smaller revisit time is needed then the STK algorithms would yield better results. To address partial coverage of a target area extra constraints could be added to define which areas are to be accessed at least once, twice or more times over the simulation period. These areas could be strategic points such as ports, airfields or choke points.

5.2 Number of Assets and Orbital Elements

Auspace has stated that the initial choices of constellation size and structure, orbit inclinations, altitudes, and RAANs. These parameters affect the coverage of, and the revisit times to, the target area. Auspace have chosen their orbital elements using rules of thumb gained through experience.

The number of times a satellite passes over the target area during the simulation period is affected by the initial RAAN of the satellite, while the access duration to the target area is affected by the inclination of the satellite used.

For the orbital elements chosen no points can be seen during passes 11, 12 and 13 of the simulation.

Possible criterion for choosing inclination, altitude and RAAN:

- Minimize the number of satellite passes where no part of the target area can be seen.
- Maximize the number of satellite passes over the target area during the 24-hour simulation.
- Minimize the number of satellites needed to perform the surveillance task through efficient constellation design.

6. Conclusions

When assessing the capabilities of small satellites a variety of algorithms need to be used to examine the satellite's performance attributes.

The percentage coverage found varied greatly between the longest ground track algorithms and the ILOG algorithms used in this report. Most notably the ILOG-2a algorithm demonstrated that if each satellite was utilized well then 8-satellites are enough to cover the target area. Whereas from Auspace's results, 16 satellites are needed for similar coverage. Ultimately, this becomes a very significant reduction in cost of producing and launching these satellites. This result has demonstrated how the use of optimisation techniques such as linear programming can successfully be employed to decrease the size of constellations designed for surveillance.

When describing the difference between ILOG-2 and ILOG-2a the quality of coverage was briefly discussed in terms of percentage coverage and revisit time to the target. By adding an extra term to the objective function the allocation of sensor swaths was changed to maximise the number of points seen and the number of times these points were seen though out the simulation. This addition to the problem formulation had a number of effects: the search time for an optimal solution was reduced and the number of points seen multiple times increased.

A study of the tradeoffs made when maximizing coverage areas while minimizing revisit times and satellite numbers for specific area targets would be of use for the assessment of small satellites as effective surveillance tools.

When assessing the use of satellites for surveillance the quality of surveillance required needs to be carefully defined. For example, is the analysed satellite system designed to search for vessels, track vessels already detected or to do both detection and tracking of vessels in the target area? Is it known how much and how often information is required to search a target area in such a way as to prevent any undetected vessels arriving in Australia? The answers to these sorts of questions provide the objectives to studies that optimise a satellite system's operation.

The quality of coverage needed is more complex than revisit time and area covered. Other issues, which affect the quality of coverage, are the satellite's resolution, the satellite's ability to operate during any weather and day or night, and the availability of ground stations to receive the information collected. The model used in this report can be extended to incorporate a more complex definition of coverage quality.

This report looked at the use of a linear optimisation technique to optimise the operation of a known constellation of satellites with known sensor types and swath settings for percentage area covered. The initial choices of constellation size and structure, orbit inclinations, altitudes, and RAANs affect the coverage of, and the revisit times to, the target area. These optimisation techniques can be extended to the optimal design as well as the optimal operation of a small satellite constellation for a particular surveillance task

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Appendix A: Coverage Results

The accesses to the target are calculated over a 24-hour period. The grid spacing used by STK is 0.5°. The following three scenarios are investigated:

- A satellite is in an orbit of 20° inclination, altitude 461.95 km and RAAN 0°.
- 8 satellites evenly spaced over a single orbital plane of inclination 20° and altitude 461.96 km. The simulation was done over a period of 24 hours using algorithm 1 of the LGT algorithm.
- 16-satellite constellation. This constellation has two orbital planes of 8 satellites. Orbital inclinations are 20° and 15°, altitudes are 461.96 km and 459 km and RAANs are 45° and 30°, respectively. These results are from algorthim 1 of the 3 LGT algorithms.

A.1. Percentage Coverage from STK Algorithms

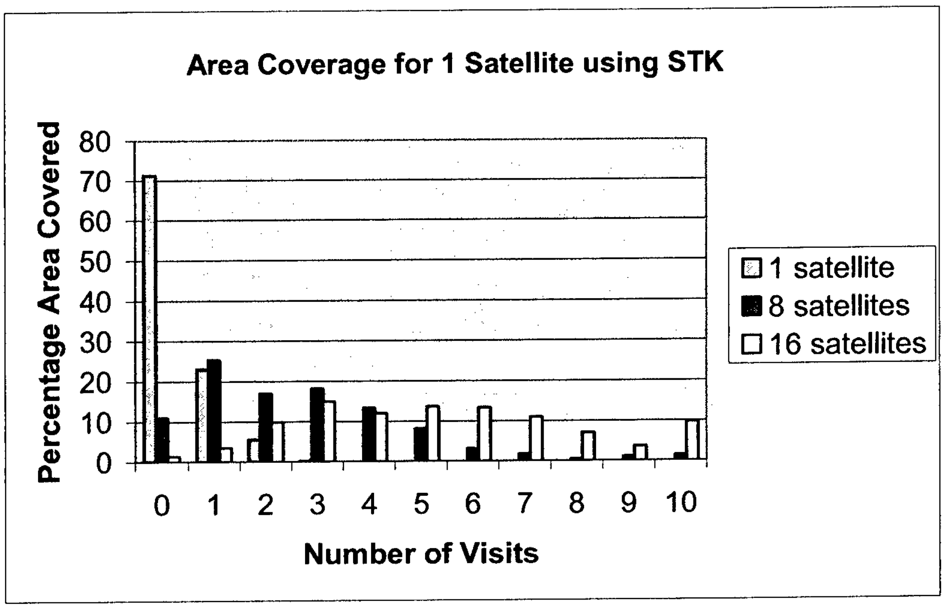

Figure 9: Area coverage for the 1 satellite scenario using the longest ground track STK –1

Table 7: Coverage results for STK Algorithms 1, 2 and Auspace results for the 8-satellite scenario.

Visits	Algorithm 1	Algorithm 2	Auspace
1	25.36	18.54	31.92
2	16.06	21.03	25.65
3	18.19	19.66	14.62
4	13.38	12.21	7.81
5	8.19	9.08	3.12
6	3.12	4.14	1.35
7	1.72	2.23	0.65
8	0.45	0.92	0.17
9	1.05	0.61	0.07
10+	1.43	0.35	0.01
Total	88.94	88.77	85.37

A.2. Percentage Coverage with ILOG Algorithms

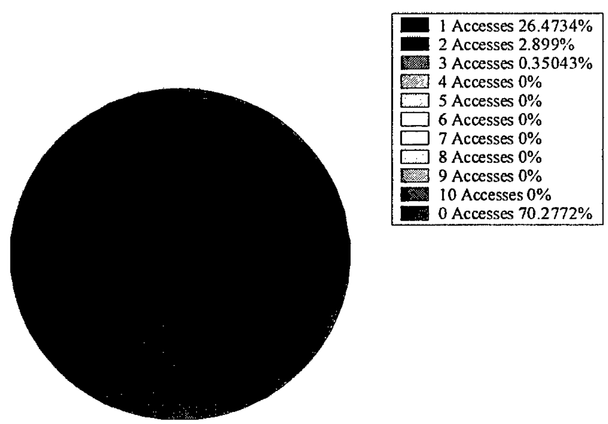

Figure 10: Percentage coverage for the 1-satellite by ILOG-1, which maximizes the area covered over a period of 24-hours.

Table 6: Percentage Area Covered for ILOG algorithms used in the 1 and 8 satellite cases.

	One Satellite Case		8-Satellite Case			
Visits	**Longest Track STK**	**ILOG**	**Longest Track STK**	**ILOG-1**	**ILOG-2**	**ILOG -2a**
1	23.07	26.47	18.54	18.60	27.84	22.52
2	5.53	2.90	21.03	24.72	39.82	34.98
3	0.16	0.35	19.66	25.77	21.12	27.21
4	0.00	0.00	12.21	15.73	6.98	12.01
5	0.00	0.00	9.08	6.63	2.17	2.10
6	0.00	0.00	4.14	1.78	0.57	0.45
7	0.00	0.00	2.23	0.25	0.19	0.06
8	0.00	0.00	0.92	0.00	0.00	0.00
9	0.00	0.00	0.61	0.00	0.00	0.00
10+	0.00	0.00	0.35	0.00	0.00	0.00
Total	28.66	29.72	89.17	93.48	98.69	99.33
Ave Revisit time	19.96 hours	21.41 hours	7.87 hours	8.83 hours	11.68 hours	10.11 hours

Table 7 Percentage area covered by the ILOG - 2 and ILOG- 2a for the 16-satellite case

16-Satellite Case			
Visits	**Longest Track STK**	**ILOG-2**	**ILOG-2a**
1	3.50	6.95	4.05
2	9.84	29.63	8.63
3	15.00	34.21	12.55
4	11.98	19.62	11.12
5	13.64	6.47	14.62
6	13.38	1.66	14.02
7	10.96	0.96	12.38
8	7.04	0.32	8.06
9	3.63	0.16	5.99
10+	9.71	0.00	8.57
Total	98.68	99.99	100.00

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19. ABSTRACT

To protect Austalia's economic concerns and its coastline from attack there is a need for surveillance of a large area of Australia's Sea Air Gap. Satellites have the advantage of viewing large areas of the earth regularly. Currently there is no indigenous facility to launch satellites dedicated to the surveillance of Australia. With the advent of new micro technology small nano/pico satellites are being built and launched at a fraction of the cost of conventional satellites. This has allowed for the invention and investigation of new concepts for satellite missions. For example Auspace (Tactical Satellites Study: Interim Report RTP-TACSAT-0001-AUS 17-April 2003) is investigating the feasiblity of the design of small satellites for short term misssions to be launched into low orbit on demand. This report investigates the use of linear programming to optimise the preformance of constellations of small satellites when the constellation design for a particular misssion is known.